EXPERIMENTAL STUDIES ON SHEAR CONNECTION BETWEEN STEEL AND LIGHTWEIGHT CONCRETE USING STUDS

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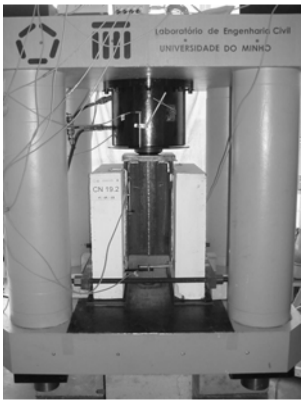
ABSTRACT

This contribution describes Standard Push-Out Tests carried out at University of Minho (UM) and the Single Push-Out Tests performed at the Institute of Structural Concrete at RWTH Aachen University using high strength lightweight concrete (HSLWC). The test configuration follows the EC4 recommendations and repeats some dispositions referred by other authors. The experimental studies carried out at RWTH and UM include tests on studs with diameters of 19, 22 and 25 mm and also tests on studs of 19 mm diameter, which are grouped in pairs. The purpose of the experiments conducted is to determine the load-bearing capacity as well as the deformation capacity of commonly used headed shear stud when using high strength lightweight concrete. The results from these tests are compared to those from the tests performed with high strength normal weight concrete (NWC).

1. INTRODUCTION

1.1 The Standard Push-Out Test (POST)

The Standard Push-Out Test (POST), according to EC 4, simulates the transfer of shearing forces in the composite joint of composite girders (Fig. 1).



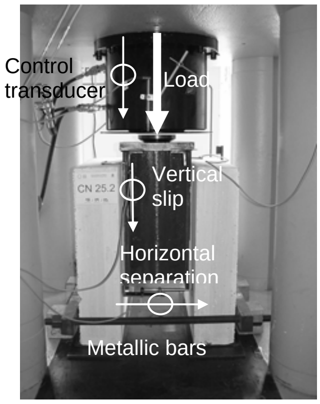
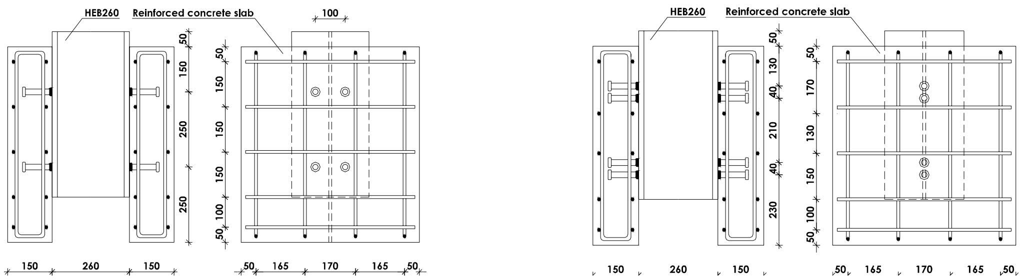


Fig. 1: Test setup and dispositions.

The dimensioning of these test specimens is matched to standard-strength concrete. By using the higher concrete-quality grades and the thereby associated reduction of the load propagation zone, the magnitude of this test specimen is no longer necessary to prevent premature failing of the concrete yet for reasons of comparability, the Push-Out Standard Test is also used where high-strength concrete is concerned. The statics of this system are not optimal. During the experiments, the steel girder shall be displaced relatively to both of the reinforced-concrete belts such that the shear connectors undergo stress of the purely shearing type. However, horizontal forces cannot be avoided between the three construction members in the practical execution of the experiment. Thus, not the ultimate shear carrying capacity of one headed stud can be determined, but an average load-bearing capacity, [1].

The test set up follows the Eurocode 4 dispositions for shear connection between steel and concrete tests, [2]. For each type of connector, the geometry of the test set-up is always the same, with variation on diameter for studs and stud disposition. The slab dimensions is $650\times600\times150$ mm^3. The slab reinforcement represented in Fig. 2 corresponds to 10 mm diameter bars. Connectors are always welded to the steel profile and later embedded on the concrete slab after concreting.



Isolated stud: ∅19, ∅22 and ∅25 mm (CN series) Double stud ∅19 mm (CDN series)

Fig. 2: Specimens geometry for experimental POST tests, according to EC4

Both slabs are concreted simultaneously in horizontal position to simulate the conditions in a real structure (composite beam or slab). This implies the cut of the steel beam in two halves. After the concrete hardening it is possible to put both slabs in vertical position and then weld the two HEB260 half webs. The concrete resistance is intended to be approximately the same. This could not be completely accomplished, because the specimens were cast in different days, but the concrete main properties were determined for all castings at the same day of the respective specimen “Push-Out” test.

1.2 The Single Push-Out Test (SPOT)

In order to obtain the characteristic curve for a single shear connector, a new shear test was developed at the Institute of Structural Concrete in Aachen. In the Single Push-Out Test (SPOT) a single shear connector can be tested individually. Here, the structural stability does not result from the symmetrical construction but from the nearly identical straining lines of the acting forces. Since the resulting lateral force during shearing does not remain at a constant level, the experimental set-up should be capable of tracking such changes without loosing its stable state of equilibrium.

A shoe enveloping the reinforced concrete was chosen as the solution (Fig. 3). Two additionally attached stirrups created a moment opposing the resulting moment ($M = 0.055\text{ m} \times F$; where 0.055 m is the distance between the straining lines). This neutralising moment adapts to every load level. Even a parallel shift in the resulting shear force (perpendicular to the shaft of the connector) is accepted by the system without any kinematic reaction. A slight twist of the steel relative to the reinforced concrete is to be expected during the experiment, but the upper stirrup of the shoe does constitute a horizontal restriction. As soon as twisting has set in, the steel nuts impact on the stirrup and form a vertical sliding bearing. As the detachment process progresses, the plate turns back to a parallel position. A falsifying influence on the load-bearing behaviour could not be seen in the series of experiments conducted, [3].

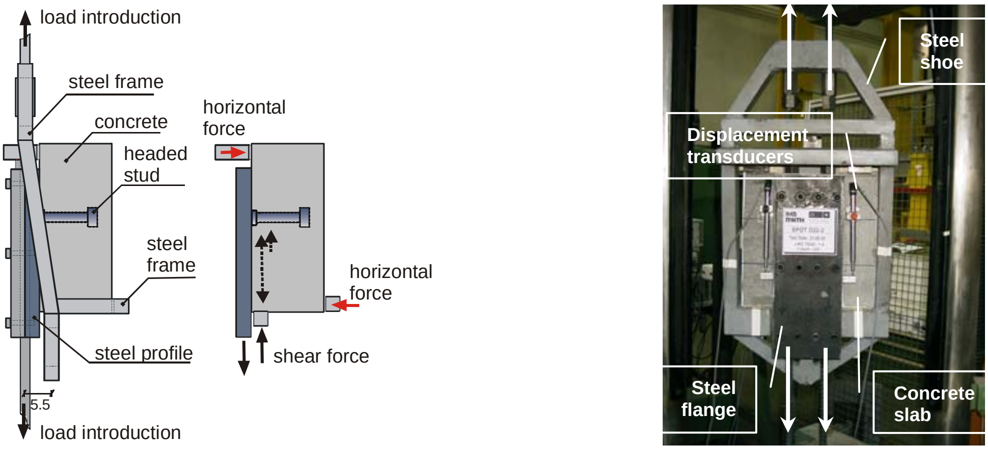
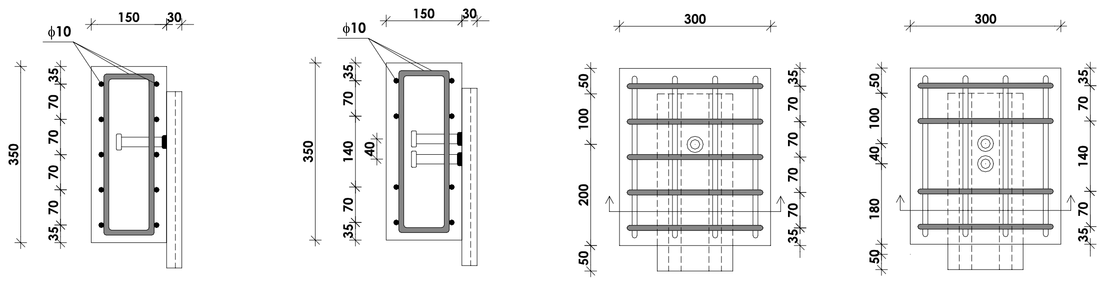


Fig. 3: Single Push-Out test: acting forces and setup, [3]

This test specimen is straightforward to fabricate, can be inserted in the testing frame by a single person and lower hydraulic loads are required compared to the Push-Out Standard Test. It is particularly suitable for high-strength concrete due to the limited volume of concrete. The SPOT specimens were fabricated according to Fig. 4 dispositions.



Side view for single stud	Side view for double stud	Front view for single stud	Front view for double stud

Fig. 4: Single Push-Out Test specimens

2. TESTS RESULTS

2.1 Materials properties

The HSLWC mixtures were defined in UM and RWTH with the available materials at each university. The POST tests used a lightweight concrete studied at the Structural Laboratory of University of Minho and for the SPOT a lightweight concrete developed at the Institute of Structural Concrete has been used. Concrete properties are not the same for both mixtures, but the values for compressive strength and elasticity modulus presented in Table 1 were determined for all castings at the same day of the respective test.

Table 1: Description of the specimens and results of Push-Out tests

Specimens	Test	Connectors disposition	Stud diameter [mm]	Concrete density [kg/m^3]	$f_{c,cylinder}$ [MPa]	$f_{c,cube}$ [MPa]	E_c [GPa]
CN 19.1 CN 19.2 CN 19.3	POST	Single	19	1895	53.7 56.0 55.4	-	24.7 24.5 24.7
CN 22.1 CN 22.2 CN 22.3	POST	Single	22	1880	58.7 55.2 54.1	-	24.9 25.7 22.4
CN 25.1 CN 25.2 CN 25.3	POST	Single	25	1819	55.3 54.6 53.4	-	24.2 24.5 22.5
CDN 19.1 CDN 19.2 CDN 19.3	POST	Double	19	1800	54.6 61.2 58.1	-	22.3 28.0 26.0
PD19-1, PD19-2	SPOT	Single	19	1800	-	94.0	23.5
D19-1, D19-2, D19-3	SPOT	Single	19	1800	-	84.6	26.6
D22-1, D22-2, D22-3	SPOT	Single	22	1800	-	78.5	25.7
D25-1, D25-2, D25-3	SPOT	Single	25	1800	-	78.5	25.7
DD19-1, DD19-2, DD19-3	SPOT	Double	19	1800	-	84.6	26.6

Steel specimens were collected from the same reinforcement and stud group used in the “Push-out” tests and later tested. Table 2 presents the corresponding results.

Table 2: Steel properties

Type of specimen	diameter	POST tests		SPOT tests	
	d [mm]	f_y [MPa]	f_u [MPa]	f_y [MPa]	f_u [MPa]
Stud	19	501	596	502	534
	22	458	559	532	548
	25	466	557	566	584
Reinforcement	10	576	675	-	-

2.2 Standard Push-out test

The load carrying capacity of one headed stud in normal weight concrete essentially results from four components: concrete compressive strength around the welded collar, shear and bending of the stud’s shank, tensile forces in the stud’s shank and friction forces between steel and concrete on the composite joint. The load carrying capacity due to friction is not considered in the performed tests because the steel surface was greased before concreting. In high strength concrete there are almost no tensile forces acting in the shank. In addition, the deformation concentrates on a small area directly above the welded collar [1]. In case of lightweight concrete this behaviour is not well known, making experimental testing necessary.

Headed studs are characterized by a high initial stiffness followed by a plastic behaviour, with a constant or slow increasing load in the plastic range. In general, the failure in high strength normal weight concrete is initiated by shearing. To prevent gaps between steel and concrete, steel bars are arranged to keep both slabs together (Fig. 1).

For each stud diameter, three specimens are tested. As shown in Table 3, the results are very similar for each group, which proves the good quality of the results. In the majority of the performed tests, shear failure is identified on studs. Failure always occurs first on one side of the specimen, even though the specimens are symmetric. An exception are the 25 mm diameter studs where concrete failure occurred in specimens CN25.2 and CN25.3. The high loads lead to severe cracking of the slabs and concrete crushing near the studs (Fig. 5). With increasing diameter the load carrying capacity of the headed stud is increasing. The concrete slab is subjected to higher stresses and thus more cracks are developing.

Specimen with 19 mm stud diameter

Specimen with 25 mm stud diameter

Fig. 5: Concrete crack patterns (POST tests)

As a result, the descending branch is softer on 25 mm diameter specimens, as failure happens with progressive cracking and crushing of the concrete slabs, without shear failure on studs. Fig. 6 presents load-slip curves for each diameter of tested stud. The load capacity increases with stud diameter, as expected, as well as slip for maximum load. There is a close relation between maximum load value and corresponding characteristic slip value. This is a closely linear relation, as presented in Fig. 8.

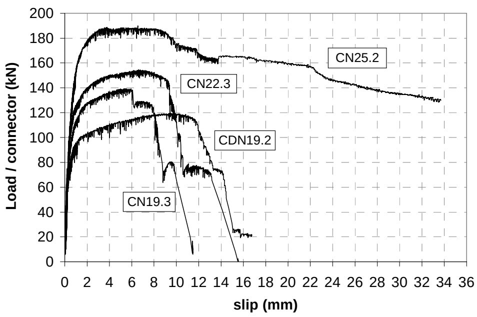


Fig. 6: Load vs. slip (POST tests)

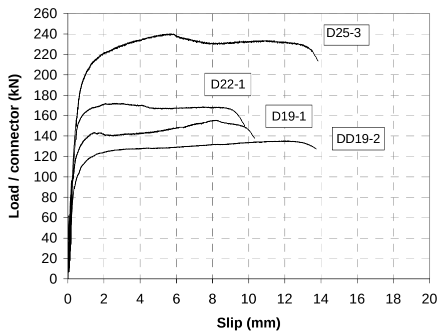


Fig. 7: Load vs. slip (POST tests)

In a further test series, two studs were welded closely together in the longitudinal direction (Fig. 2). A loss of load capacity is observed for this case. This disposition results in a reduction of 14% of the maximum load value. However, this results in an increase in deformation capacity and thus an increase of 22% is achieved (Fig. 6).

Paragraph 6.1.2(3) of Eurocode 4 [2] recommends a characteristic plastic deformation value, δ_k of 6mm for stud connectors, if a ductile behaviour is intended. This limit is verified for most of the tested specimens, guarantying ductility. Results of tests performed in the RWTH, [3], with HSNWC reveal that this minimum deformation value of 6 mm is not always achieved. However, it is important to refer that this aspect is more relevant when the connection elastic-plastic behaviour is assumed.

The determination of the characteristic slip value results in considerable high values of elastic slip, especially for the smaller diameters, as was verified during calculations. This may modify the results interpretation.

Table 3. Experimental results for POST tests

Specimen Ref[a]	P_{max} [kN]	P_{medium} [kN]	P_k [kN]	$\delta_{elast,i}$ [mm]	δ_{ki} [mm]	δ_k [mm]
CN 19.1	141.0			1.85	6.74	
CN 19.2	140.4	140.2	125.4	2.11	6.09	5.42
CN 19.3	139.4			1.77	6.02	
CN 22.1	155.1			*	*	
CN 22.2	156.0	155.2	139.1	1.40	7.26	6.53
CN 22.3	154.5			1.94	7.44	
CN 25.1	192.1			1.35	11.45	
CN 25.2	190.0	192.2	177.0	1.54	10.25	9.23
CN 25.3	194.5			1.17	11.84	
CDN 19.1	120.3			2.63	7.37	
CDN 19.2	119.6	120.6	107.7	3.08	8.83	6.63
CDN 19.3	122.0			2.69	8.12	

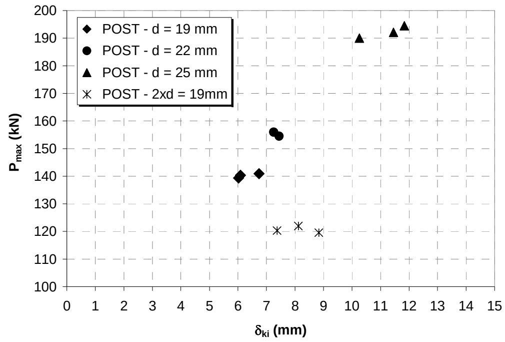


Fig. 8: Maximum load and corresponding slip (POST tests)

* Deformation control on CN22.1 was not properly accomplished; therefore, this result was not considered.

Where: P_{max} maximum load (for each specimen)

P_k $= 0.9\ P_{max}$ (where P_{max} is the minimum value for a group of three similar specimens)

$\delta_{elast,I}$ elastic slip for load P_k

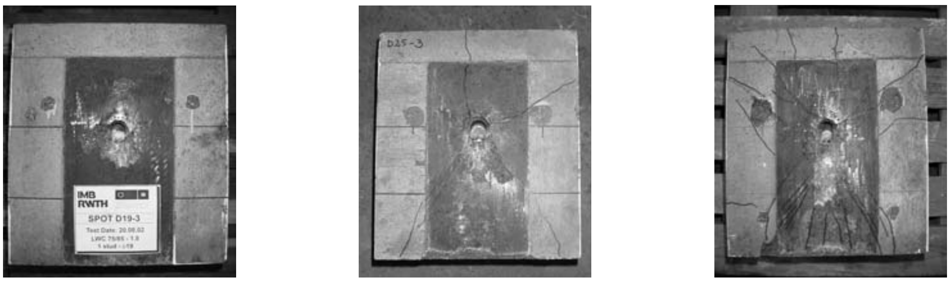
δ_{ki} – plastic slip for load P_k

δ_k 0.9 * minimum slip for a group of three similar specimens

Comparing these results with others found in the bibliography for HSNWC, it is noticeable that HSLWC specimens show higher deformation values. On the other hand, maximum load values are smaller. It is presumable that the observed differences result principally from the differences between concrete elasticity modulus and tensile strength of the two materials. If the elasticity modulus is higher, then the connection behaviour is less ductile and shear failure will occur in the connector. On the other hand, if the elasticity modulus is lower, the behaviour is more ductile and the tensile component tends to increase.

2.3 Single Push-Out Test

Headed studs with a diameter of 19, 22 and 25 mm were tested. For each diameter, a series of three specimens was tested. In all the series of SPOT tests performed, shear failure occurred. In all the tested specimens a concrete wedge developed in front of the welded collar. As diameter increases, the higher loads also lead to cracking of the slabs (Fig. 9). This cracking is accentuated for D25 and DD19 series. The cracking diffusion, however, is not so important as was verified during POST tests. One possible reason is the higher compressive strength of SPOT specimens concrete.



D19 D25 DD19

Fig. 9: Concrete crack patterns (SPOT tests)

Since stud failure occurred, one can assume that the carrying capacity does not depend on the concrete strength, although is an important parameter for the connection’s behaviour. Table 4 and Fig. 10 present the results from the performed SPOT tests. At approximately 85% of the characteristic load a loss of stiffness can be observed. The final phase of loading is characterized by the increase in slip for an approximately constant load. The loss in stiffness is more noticeable in the SPOT tests than in POST tests.

Table 4: Experimental results for SPOT tests

Specimen Ref[a]	P_{max} [kN]	P_{medium} [kN]	P_k [kN]	$\delta_{elast,i}$ [mm]	δ_{ki} [mm]	δ_k [kN]
PD19-1	155.9	158.4	140.3	1.00	6.75	6.08
PD19-2	160.9			0.69	10.15	
D19-1	155.4			1.06	9.15	
D19-2	153.6	156.2	138.2	0.82	5.99	5.39
D19-3	159.5			1.15	12.15	
D22-1	172.1			0.64	8.98	
D22-2	180.5	179.9	154.8	0.73	6.88	6.19
D22-3	187.1			0.93	9.13	
D25-1	238.2			1.89	12.03	
D25-2	243.0	240.4	214.4	2.25	10.58	9.52
D25-3	240.2			1.48	12.28	
DD19-1	138.1			1.08	10.81	
DD19-2	135.1	137.6	121.6	1.54	12.20	9.72
DD19-3	139.5			2.43	15.77	

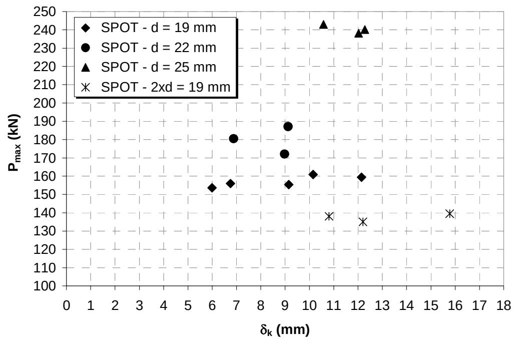


Fig. 10: Maximum load and corresponding slip (SPOT tests)

The load carrying capacity increases with stud diameter as it has been recognized in the Push-Out Standard Tests. However, the characteristic slip does not increase with increasing diameter, which was not expected. The association of two closely welded studs results in a decrease in ultimate load of 13 %, very similar to the decrease measured for POST tests. The lost of load capacity comes along with an increase in deformation of 70%, which is much more than verified in POST tests. The relation between maximum load value and corresponding characteristic slip value (value of slip determined for the characteristic load) cannot be defined as in the POST, as there is some variability in the specimens deformation capacity.

2.4 Comparison between POST and SPOT tests

A comparison of the test results from POST and SPOT with headed studs with a diameter of 19, 22 and 25 mm respectively showed, that 10 to 20 % higher loads are achieved in the SPOT. On the one hand this results from the higher concrete strength in the SPOT and, on the other hand, from the pure shear loading in the SPOT.

Comparing these results with others presented in the bibliography for HSNWC, it is noticeable that HSLWC specimens show higher deformation values coming along with a decreased ultimate load. It is presumable that the observed differences principally result from the differences between concrete elasticity modulus and tensile strength of the two materials. If the elasticity modulus is higher, then the connection behaviour is less ductile and shear failure will occur in the connector. On the other hand, if the elasticity modulus is lower, the behaviour is more ductile and the tensile component tends to increase.

As registered on Table 5, the differences on characteristic load capacity between SPOT and POST for LWC are of about 10%, except for tests with stud diameter of 25 mm. This difference is similar the one previously obtained for POST and SPOT performed with NWC, [3]. This observation confirms the validity of choosing SPOT tests for LWC, confirming this type of experimental test as an alternative to POST tests.

As referred before, two POST specimens with 25 mm studs failed due to cracking and crushing of the concrete slabs. This explains the lower value for the $P_{k,POST}$ / $P_{k,SPOT}$ relation presented in Table 5.

Table 5: Comparison between POST and SPOT tests, for lightweight concrete

stud type	P_k (POST-LWC) / P_k (SPOT-LWC)	δ_k (POST-LWC) / δ_k (SPOT-LWC)
KBD 19	0.908	1.005
KBD 22	0.898	1.054
KBD 25	0.798	0.969
Double KBD 19	0.886	0.682

In terms of slip, there is a good agreement of results between the two types of shear test, with exception to the double connector option. However, the tendency is to have higher deformation values in SPOT tests. There is higher variability in the SPOT test results, but the characteristic values resulted from the smaller slip from a group of three tests (Fig. 11).

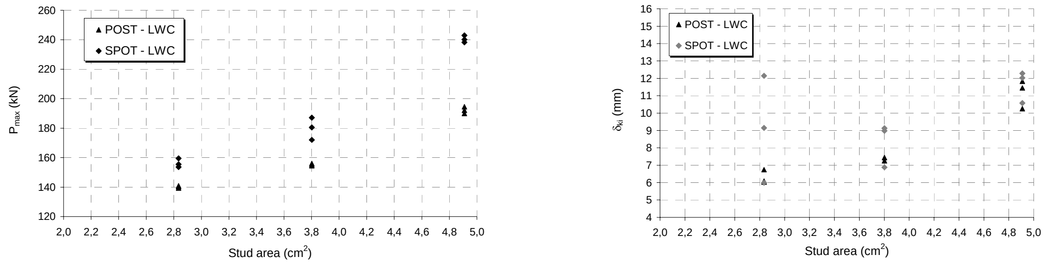


Fig. 11: Load and slip vs. stud area

3. SUMMARY

As observed and measured during the series of Push-Out tests performed, HSLWC is adequate to be used in composite structures. The results show some loss of load capacity, compared to NWC specimens, but a good general behaviour is noticeable, with a tendency of an increase in deformation capacity. The Single Push-Out test performed at the Institute of Structural Concrete in Aachen [3] proved to be a good alternative to the Push-Out Standard Test, when LWC is used and the resulting differences match the ones already observed for NWC. The type of failure observed in the POST for 25 mm headed studs shows that a HSWLC (with compressive strength at least higher than 55 MPa) should be used in order to generate steel failure. In general, the connectors showed a ductile behaviour, as the plastic slip exceeds the value of 6 mm which are demanded in EC4 [2].

REFERENCES

[1] Hegger, J.; Goralski, C.; Rauscher, S. and Kerkeni, N.: 2004, "Finite Elemente Berechnungen zum Trag- und Verformungsverhalten von Kopfbolzendübeln", *Stahlbau 73*, Vol.1, pp. 20-25.

[2] Eurocode 4, ENV 1994: Design of composite steel and concrete structures, CEN.

[3] Döinghaus, P.: Zum Zusammenwirken hochfester Baustoffe in Verbundkonstruktionen, PHd Thesis, Institute of Structural Concrete, RWTH Aachen, 2001.

[4] Valente, I.; Cruz, P. J. S.: "Caracterização da ductilidade de ligações aço-betão leve com conectores tipo perno", 4º Congresso de Const. Metálica e Mista, 4-5/12/03, Portugal.

KEYWORDS

Composite structures; shear connection; lightweight concrete; load-bearing capacity; slip.